Received: 18 May 2016 Revised: 28 July 2016 Accepted article published: 30 August 2016 Published online in Wiley Online Library: 20 October 2016

(wileyonlinelibrary.com) DOI 10.1002/ps.4424

Value of neonicotinoid seed treatments to US soybean farmers

Terrance Hurley[a*] and Paul Mitchell[b]

Abstract

BACKGROUND: The benefits of neonicotinoid seed treatment to soybean farmers have received increased scrutiny. Rather than use data from small-plot experiments, this research uses survey data from 500 US farmers to estimate the benefit of neonicotinoid seed treatments to them. As seed treatment users, farmers are familiar with their benefits in the field and have economic incentives to only use them if they provide value.

RESULTS: Of the surveyed farmers, 51% used insecticide seed treatments, averaging 87% of their soybean area. Farmers indicated that human and environmental safety is an important consideration affecting their pest management decisions and reported aphids as the most managed and important soybean pest. Asking farmers who used seed treatments to state how much value they provided gives an estimate of $US 28.04 ha^{-1} treated in 2013, net of seed treatment costs. Farmer-reported average yields provided an estimated average yield gain of 128.0 kg ha^{-1} treated in 2013, or about $US 42.20 ha^{-1} treated, net of seed treatment costs.

CONCLUSION: These estimates using different data and methods are consistent and suggest the value of insecticide seed treatments to the US soybean farmers who used them in 2013 was around $US 28–42 ha^{-1} treated, net of seed treatment costs.

Supporting information may be found in the online version of this article.

Keywords: insecticide; soybean aphid; survey data

1 INTRODUCTION

Neonicotinoid insecticides are among the most widely adopted insecticides for managing insect pests in annual and perennial crops worldwide.[1] The nitroguanidine neonicotinoid insecticides clothianidin, imidacloprid and thiamethoxam are the insecticides most used by US commodity crop farmers in terms of area treated.[2] In addition to controlling insect pests and protecting yields, the management benefits of neonicotinoid insecticides include application flexibility and a diversity of active ingredients with activity against several economically important orders of insect pests.[1,3,4] Approved application methods include seed treatments, foliar sprays, soil drenches, granules, injection and chemigation.[3] Further encouraging their adoption, the US Environmental Protection Agency (EPA) has classified several neonicotinoids as conventional reduced-risk or organophosphate alternatives since 2001.[5] In the United States, their use in major commodity crops such as maize, soybean, wheat, cotton and sorghum is almost exclusively as seed treatments, although some foliar application occurs on cotton and soybean. The 2010–2012 average in the United States was 54.8×10^6 ha treated annually with neonicotinoid insecticides in these crops, of which almost 97% was applied as seed treatments, while globally 60% of neonicotinoids are applied as seed treatments.[1,2]

Neonicotinoids have been detected in surface water, groundwater and soil dust, which, when combined with known environmental risks, has led to increased scrutiny.[6–9] Specific concerns over their effects on non-target insect species have largely focused on bees, especially managed honey bees (*Apis millifera* L.), owing to recent documented declines in populations of multiple bee species.[9,10] While a variety of factors contribute to these observed population declines, the role of pesticides, especially neonicotinoids, has received intense attention.[10–15] Managed bees have multiple pathways for exposure to neonicotinoid insecticides, but their highest levels of insecticide exposure and risk appear to come from pyrethroid insecticides targeting mosquitoes and other nuisance pests.[16,17] The need to clarify the contributions of neonicotinoids to bee declines relative to other factors has been recognized.[10,18]

The Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) obligates the EPA to balance between risks and benefits when making pesticide registration decisions.[19] Much of the benefit evidence for neonicotinoid seed treatments has come from small-plot field experiments examining the impact of neonicotinoids on yields for a variety of crops in the United States.[20–25] As with all scientific methodologies, small-plot studies have limitations. For example, the limited number of research sites and years does not fully capture the range of spatial and temporal variation in weather, soil and terrain; plots are often managed under

* Correspondence to: T Hurley, Department of Applied Economics, University of Minnesota, 1994 Buford Avenue, St. Paul, MN 55108, USA. E-mail: tmh@umn.edu

a Department of Applied Economics, University of Minnesota, St. Paul, MN, USA

b Department of Agricultural and Applied Economics, University of Wisconsin-Madison, Madison, WI, USA

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ideal conditions that do not reflect the practical constraints faced by farmers; plus plots are subject to edge and other interplot effects.[26–29] Thus, while small-plot experiments have value, opportunities exist to expand further our knowledge of the benefits of neonicotinoid seed treatments by also taking advantage of other scientific methodologies. For example, meta-analysis of small-plot studies can help to develop a more integrated assessment of how the yield benefits of neonicotinoid seed treatments vary across the broader landscape.[30,31]

The primary objective of this research is to gain a further understanding of the benefits of neonicotinoid insecticide seed treatments to US soybean farmers. This objective was accomplished using telephone survey data collected from a stratified random sample of US soybean farmers. The survey instrument elicited information on a farmer's 2013 soybean pest management practices, pest management concerns and average soybean yields. Farmers who reported using insecticide seed treatments in 2013 were also directly asked to state their evaluation of all the benefits and costs seed treatments provided to them in monetary terms. Multiple regression analysis was used to evaluate how seed treatment use, the stated value of seed treatments and the effect of seed treatments on yields varied by farmer and farm operation characteristics. The secondary objectives of this research were to document which insect pest species are of greatest concern to US soybean farmers and which sources of pest management information are key sources for these farmers.

This research complements previous small-plot research on the benefits of neonicotinoid seed treatments in several ways. Firstly, it provides a broader evaluation of benefits that extends beyond how seed treatments affect yields by asking farmers to assign a monetary value to all the additional benefits and costs seed treatments provided to them. The use of pesticides reduces the riskiness of production, which provides non-monetary benefits such as 'piece of mind' to farmers.[32] There is evidence from the rapid adoption of herbicide-tolerant soybean varieties that having more flexible and convenient pest management options also provides non-monetary benefits to farmers.[33,34] Alternatively, the environmental and health concerns a farmer has with using pesticides can impose non-monetary costs that counteract potential yield, risk and other benefits of the insecticide's use.[35] These types of non-monetary benefit and cost cannot be measured by only evaluating how seed treatments affect yields. Secondly, the research provides an evaluation of the yield benefits of seed treatments to US soybean farmers, taking into account actual production environments, management practices and practical constraints they faced in 2013.

The research complements, rather than replaces, previous small-plot yield research because the survey method employed here has its own limitations. For example, the survey was not a controlled experiment, which precludes definitive causal inferences, although there are statistical techniques for testing causality.[36] Asking individuals to assign monetary values to potentially non-monetary benefits such as those associated with less risky production and increased flexibility can be problematic. However, a large literature exists, particularly in environmental economics, on how to obtain reliable information,[37] which a number of studies have successfully adapted to measuring the benefits of pest management to farmers.[35,38–42] All surveys can suffer from non-response bias because participation is voluntary and some farmers may choose not to participate for reasons that are systematically related to the research objectives.[36] Therefore, the results of this survey are best used in conjunction with small-plot experimental results in order to gain a better understanding of the mosaic of benefits and risks neonicotinoid insecticides provide across a farm landscape that is both socioeconomically and environmentally diverse.

2 MATERIALS AND METHODS

2.1 Farmer survey

The primary data used for this research are from a telephone survey of US soybean farmers. Market Probe (http://www.marketprobe.com/), a professional market research firm with an expertise in farmer surveys, was contracted to conduct the survey in February and March of 2014. The sampling design targeted 500 completed surveys, a sample size comparable with similar studies that have successfully explored how farmers value alternative pest management practices.[35,39,43] To improve the efficiency of our sampling effort, we stratified by state. Fourteen states accounting for 90% of the 2013 soybean-planted area in the United States were identified for sampling (Fig. 1).[44] The number of survey completions targeted from each of these states was initially set in proportion to the state's 2013 soybean-planted area.[45] To ensure adequate coverage across sampled states, 13 and 11 observations were added to the survey completion targets for Wisconsin and Michigan, respectively, by reducing the survey completion targets for Iowa and Illinois by 12 each. Market Probe then randomly telephoned soybean farmers in a state until its completion target was reached. All farmers were offered \$US 10 to encourage participation, compensate for their time and reduce the potential for non-response bias.

The survey instrument was designed in consultation with Market Probe and technical experts from the three registrants of the neonicotinoid insecticides commonly used in US seed protection products (Bayer, Syngenta and Valent). Firstly, the survey screened participants to ensure that they were not a chemical or seed company employee, were the person primarily responsible for crop management decisions and had planted at least 100 ha of soybeans in 2013 (see the supporting information for the complete survey script).

The survey then asked several questions about the 2013 growing season, including: farmer and farm operation characteristics (e.g. education, years of experience, total cropped area, tillage systems used and crops planted); average production costs (\$US ha^{-1}), average yield (kg ha^{-1}) and crop price (\$US Mg^{-1}); actively managed and most important insect pests; sources of insect management advice; specific pest management practices and products used; most important non-monetary considerations when making insect management decisions; biggest insect pest management concerns in soybean; perceived value of pest management practices that were used by the respondent in 2013. The survey used non-SI units, as these were more familiar to respondents. As such, direct quotes from the survey also use non-SI units, while results are converted to SI units. Survey data were supplemented with 2013 USDA National Agricultural Statistics Service (NASS) county average yield data.[44]

Information from this survey that was of primary interest for this analysis is the use of an insecticide seed treatment and its perceived value. Farmer-reported average soybean yield was also of interest. Regression analysis was used to explore how variation in farmer use, perceived value and average yield related to farmer and farm operation characteristics and the most important non-monetary considerations in a farmer's insect pest management decisions.

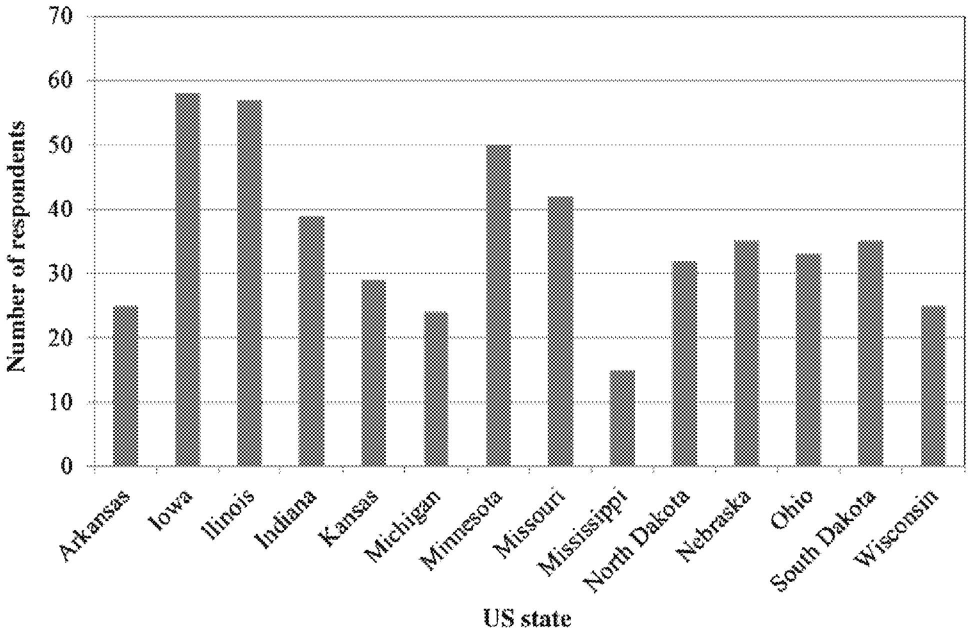

Figure 1. Number of soybean farmer responses by US state to a telephone survey (responses = 500).

2.2 Response variables

Farmer seed treatment use was examined with responses to the question: 'Were any of your soybean acres in 2013 planted with seed that had an insecticidal seed treatment?'. Responses were coded as 0 for 'No' and 1 for 'Yes' and analyzed using a probit regression model estimated with STATA's probit command.[46] Farmer use of seed treatments was also examined using the proportion of their soybean area planted with treated seed, conditional on a farmer indicating treated seed was used in 2013. This variable was calculated from their responses to two questions: 'How many acres of soybean did you plant in 2013?' and 'How many of these acres were planted with seed that had an insecticidal seed treatment?'. Because this proportion was bounded between 0 and 1 with frequent observations at 1, a tobit regression model was estimated with STATA's intreg command.[46]

The additional value per hectare of all the benefits that a seed treatment provided, conditional on a farmer indicating treated seed was used in 2013, was directly elicited based on their responses to the following question:

> Please think carefully about all the reasons why you chose to plant soybean with an insecticide seed treatment in 2013 and what else you could have done to manage insects instead of using an insecticide seed treatment. Compared to these alternatives, what additional value would you say using an insecticide seed treatment provided to you per acre of treated corn?

- not more than $US 5 per acre,
- more than $US 5, but not more than $US 10 per acre,
- more than $US 10, but not more than $US 15 per acre,
- more than $US 15, but not more than $US 25 per acre,
- more than $US 25 per acre.

Because farmers were offered ranges with clear boundaries and only had to indicate which range their individual value was in, the analysis used interval regression which was also implemented with STATA's intreg command.[46] The order of the five ranges was read in reverse to a random sample of farmers in order to detect 'starting point' bias.[47] A test of the no 'starting point' bias null hypothesis[48] could not be rejected ($P = 0.116$), which increases confidence in the reliability of the farmers' responses.

The final response variable of interest was the reported average yield, obtained from the question: 'On average, how much per acre would you say your 2013 soybean yielded? That is, how many bushels per acre, on average, across your entire operation?'. Given the continuous nature of soybean yields, ordinary least squares (OLS) regression was used with STATA's regress command and the vce(robust) option.[46] The vce(robust) option produces standard errors that are robust to heteroscedasticity, a common occurrence with yield data, including the yield data here based on a variety of diagnostic tests.

Owing to oversampling in Wisconsin and Michigan and undersampling in Iowa and Illinois, STATA's probit, intreg and regress commands were executed using sampling weights. The sampling weights were constructed to make a respondent's proportion of the state's sampled soybean area proportional to the state's total 2013 soybean area, such that the sum of weights for respondents in a state equaled the state's total 2013 soybean area. All four models were also estimated with state-level fixed effects to control for factors that may lead to systematic differences in soybean production across states. Additional technical details on the analysis can be found in the supporting information.

2.3 Control variables

Farmer and farm characteristics included the farmer's level of education and years of farming experience and the total crop area in 2013. Educational attainment measures broadly applicable skills and knowledge that an individual has obtained, while farming experience measures skills and knowledge that are specifically applicable to the farmer's chosen occupation. Both are often found to relate to a farmer's management decisions and farming outcomes. Total cropland is a common measure of farm size that is also often found to relate to a farmer's management decisions and farming outcomes, likely owing to the time constraints and complexities it imposes. To control for spatial heterogeneity in the farming environment, we include the 2013 NASS county average yield.[44] Because about 5% of respondents came from counties without a 2013 NASS-reported average yield, we included an indicator variable equal to 1 if the county average yield was not reported by NASS in 2013 and 0 otherwise, which preserved sample size with a loss of only one degree of freedom. The 10 year (2004–2013) NASS county average and the standard deviation were also explored as possible controls, but had less explanatory power and were highly correlated with the 2013 NASS county average yield.

To measure the importance of various non-monetary factors on pest management decisions, farmers were asked to rate the importance of 20 different items on a four-point scale, with 1 equal to not important, 2 equal to somewhat important, 3 equal to important and 4 equal to very important. These items included: protecting yield; cost; family and worker safety; protecting beneficial insects; saving time and labour; public safety; protecting wildlife; crop marketability; convenience; improving crop health; reducing equipment wear and tear; simplicity; flexibility; reducing scouting; having consistent insect control; having long-lasting insect control; improving crop stand; being able to plant early; replant and other product guarantees. These factors were selected for the survey on the basis of important sources of non-monetary benefits identified in previous research.[33,49–51] Additional factors not identified in previous research but considered potentially important in this case included: improving crop stand; improving plant health; replant or other product guarantees; crop marketability; protecting beneficial insects.

Owing to high correlation among farmer responses to these 20 items, factor analysis was used to reduce the number of highly correlated variables for regression.[52] The premise of factor analysis is that underlying unobserved factors drive individual responses to the various survey items, resulting in correlation across responses. Factor analysis provides a tool to identify these underlying factors and create new variables that measure these factors for subsequent interpretation and analysis. STATA's factor command was used to perform the factor analysis.[46] The parallel analysis paradigm,[53] which performs well in simulation studies and is considered less ad hoc and subjective than the widely used Kaiser rule or Cattell's scree test,[54] was used to identify four statistically significant factors. After performing a varimax rotation to facilitate interpretation of these four factors, STATA's predict command was used to generate scores for each factor and farmer using the default regression method.[46] These factor scores provide controls for systematic differences in farmers' attitudes regarding various non-monetary factors that influence their insect pest management decisions.

A farmer's decision to use an insecticide seed treatment was also used to explain variation in reported average soybeans yields. Using a farmer's seed treatment use to explain yield variation is potentially problematic. While it may be true that the use of a seed treatment boosts a farmer's yields, it might also be true that farmers with relatively high yields are more inclined to use seed treatments than farmers with relatively low yields because they have more to protect. To rule out this reverse causality, we initially conducted the analysis using instrumental variable techniques with the ivreg2 command in STATA.[55,56] The results of this analysis are reported in the supporting information and indicate that reverse causality was not a significant issue, and so OLS regression is preferred to instrumental variable regression owing to its greater efficiency.

3 RESULTS AND DISCUSSION

3.1 Descriptive overview

The average farm size was more than 600 ha, with responses ranging from about 100 to 6475 ha and soybean making up just more than 40% of this total area (Table 1). Total leased hectares operated were on average about the same as the average hectares of soybeans. In terms of other crops, 88% of farmers planted maize, 31% planted wheat, 11% had hay/alfalfa and more than a third had livestock (Table 1). On average, farmers had completed the equivalent to an associate or technical degree and

Table 1. Descriptive statistics for US soybean farmer and operation characteristics in 2013 for telephone survey respondents

Variable	Mean	Standard deviation	Minimum	Maximum	N
Total cropped area (ha)	611	638	101	6475	480
Soybean-planted area (ha)	273	327	101	5513	500
Leased area (ha)	270	449	0	6475	492
Livestock on operation:					
% of farmers	37.4				500
Other crops planted:					
% planting hay/alfalfa	11.4				500
% planting cotton	2.6				500
% planting maize	87.8				500
% planting wheat	30.6				500
% planting other crops	10.8				500
Education (years)[a]	14.0	2.1	10	18	493
Years farming (years)	33.2	14.2	2	77	496
Average soybean yield (kg ha^{-1})	3397	3173	67	50 438	495
Average county yield in 2013 (kg ha^{-1})	2935	596	784	4012	472
% Unreported 2013 average county yield (Yes = 1)	5.6				500

[a] Did not complete high school = 10 years, high school = 12 years, some college = 14 years, vocational/technical training = 14 years, college graduate = 16 years, advanced degree = 18 years.

Table 2. Summary of US soybean farmer survey responses for insect pests actively managed and the percentage actively managing each pest and reporting each pest as the most important to manage ($N = 500$)

Insect pest	Actively managed	Most important
Aphid (Hemiptera: Aphidoidea)	38.2	31.0
Beetle (Coleoptera)[a]	11.6	6.2
Mite (Acari: Tetranychidae)[b]	8.0	3.6
Stink bug (Hemiptera: Pentatomidae)[c]	6.2	3.6
Japanese beetle (*Popillia japonica* Stål)	4.2	2.2
Nematode (phylum Nematoda)	3.8	2.4
Armyworm (*Spodoptera* spp.)[d]	3.4	2.0
Grasshopper/cricket (Orthoptera)	2.4	1.0
Wireworm (Coleoptera: Elateridae)	2.0	0.8
Three-cornered alfalfa hopper (*Spissistilus festinus* Say)	1.4	0.4
Soybean podworm (*Helicoverpa zea* Boddie)	1.2	0.6
Grub (Coleoptera: Scarabaeidae)	0.8	0.0
Seed maggot (*Delia platura* Meigen)	0.8	0.4
Bugs (Hemiptera)	0.6	0.6
Loopers (Lepidoptera: Noctuidae)	0.6	0.0
Cutworms (Lepidoptera: Noctuidae)	0.6	0.4
Budworms (*Heliothis virescens* Fabricius)	0.2	0.0
Rootworms (*Diabrotica* spp.)	0.2	0.2
Stem weevil (Coleoptera: Curculionoidea)	0.2	0.2
Caterpillars (Lepidoptera)	0.2	0.0
Worms (Lepidoptera)	0.2	0.0

[a] Including bean leaf beetle (*Cerotoma trifurcata* Förster), blister beetles (Meloidae), Mexican bean beetle (*Epilachna varivestis* Mulsant), Colorado potato beetle (*Leptinotarsa decemlineata* Say) and flea beetles (Alticini).
[b] Including two-spotted spider mite (*Tetranychus urticae* Koch).
[c] Including green stink bug (*Chinavia halaris* Say), brown stink bug (*Euschistus servus* Say), red-shouldered stink bug (*Thyanta custator custator* Fabricius), southern green stink bug (*Nezara viridula* Linnaeus), redbanded stink bug (*Piezodorus guildinii* Westwood) and rice stink bug (*Oebalus pugnax* Fabricius).
[d] Including beet armyworm (*Spodoptera exigua* Hübner), fall armyworm (*Spodoptera frugiperda* J.E. Smith) and yellowstriped armyworm (*Spodoptera ornithogalli* Guenée).

had been farming for just over 30 years. The average reported yield was 3397 kg ha^{-1}, which is substantially larger than the average of the 2013 NASS county average yields of 2935 kg ha^{-1} in these respondents' counties. However, these self-reported yields include some obvious outliers (e.g. average yield well in excess of 50 000 kg ha^{-1}). Dropping the lowest and highest 1% of these reported yields, the average was 3165 kg ha^{-1}, with a standard deviation of 874.7 kg ha^{-1}, which is more consistent with the NASS 2013 average county yields given that our sample was restricted to farmers with greater than 100 ha of soybean. Therefore, the yield regression analysis excludes observations falling outside the 1st and 99th percentiles of reported yields.

The results in Table 2 show that US soybean farmers actively managed a wide range of insect pests. Still, aphids were by far the most important insect pest, specifically the soybean aphid (*Aphis glycines*). Almost one-third of US farmers reported aphids as their most important pest; beetles, mites and stink bugs of various types were other important pests. Note that these data are observational – the outcome of farmers actively managing pests in soybean and other crops. These data are not an experimental sample of which pests would cause economic damage if left untreated, but rather the outcome of the interaction of pest pressure, human pest management actions and cropping choices. Farmer pest management practices have been shown to impact regional soybean aphid population dynamics,[57] which provides empirical evidence that the reported pest pressures in Table 2 are the outcome of both of these pest management practices and the underlying population dynamics.

Table 3 shows that insecticide seed treatments were an important control option for farmers in 2013. Just more than half of the farmers employed seed treatments on at least some portion of their soybean area. Furthermore, farmers that used treated seed in 2013 on average planted 87% of their soybean area with treated seed. With about half of the farmers planting 87% of their soybean with treated seed, the total soybean area planted with treated seed was 45%. Comparable data for foliar-applied insecticides reveal greater reliance on seed treatments. In 2013, 23% of soybean farmers used foliar applications, on 70% of their planted area on average, so that 16.2% of the surveyed soybean area was treated with foliar insecticides, most of which were pyrethroids and organophosphates.[58]

Figure 2 summarizes farmer responses to the perceived additional value of all the benefits that insecticide seed treatments provided to farmers who used them. The most common responses were \$US 5–10 acre^{-1} and \$US 10–15 acre^{-1} (\$US 12.36–24.71 ha^{-1} and \$US 24.71–37.07 ha^{-1}), with about 30% of farmers choosing each range. One in ten farmers indicated that they did not know how much additional value insecticide-treated seed had provided.

Figure 3 summarizes the sources of pest management advice that soybean farmers used. They rely roughly equally on seed/chemical company representatives, crop consultants and agricultural retailers, with almost one-third of farmers reporting each as an important source of information. These results suggest that the private sector has a more direct impact on farmer pest management decisions than the public sector (i.e. university extension). These results are consistent with findings that extension and other public sector scientists currently have a less direct influence on farmers and more influence on those who connect to farmers, such as consultants and retailers, and a role as third-party evaluators of company reports.[59,60] The implication is that the private sector has a key role to play in any program or policy intended to change farmer pest management practices, because

Table 3. Insecticide soybean seed treatment use by surveyed farmers

% Using treated seed	Mean	Standard deviation	Minimum	Maximum	N
% of surveyed farmers	51.4				494
% of surveyed soybean area	44.6	46.8	0.0	100.0	494
% of soybean area for farmers using treated seed	86.8	24.2	3.3	100.0	254

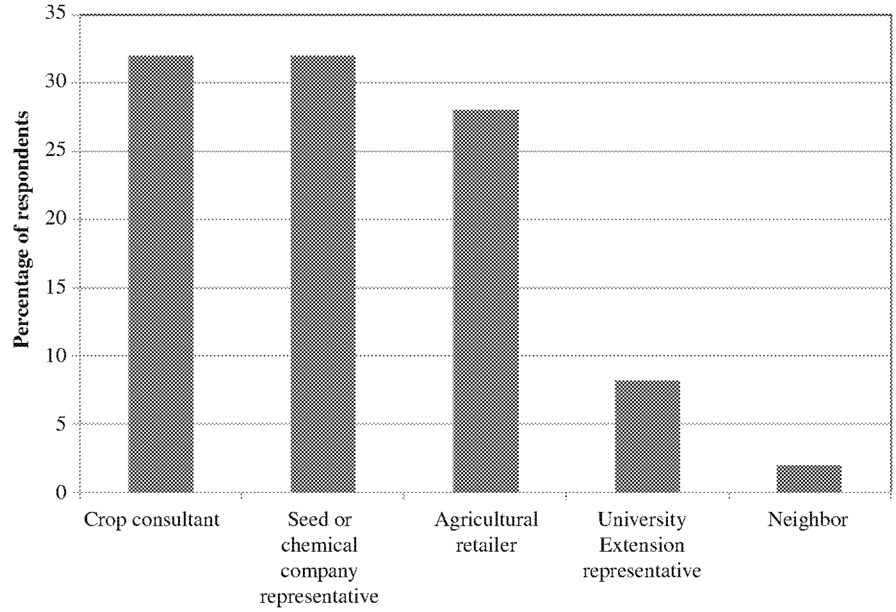

Figure 2. Reported sources of insect pest management information used by US soybean farmers in 2013 based on a telephone survey (responses = 500).

it often serves as a conduit for university research and outreach to farmers and other agricultural professionals.

3.2 Factor scores

Farmers were asked to rate the importance (on a four-point scale) of 20 different items they might consider when making insect management decisions. The 20 items and the proportion of responses in each category are reported in Table 4. Items with the highest percentage for 'very important' were 'family and worker safety' at 67%, while 'protecting yield' was second, with 62% of farmers reporting it as 'very important'. Third was 'having consistent insect control' at 58%, fourth was 'cost' at 56% and 'protecting water quality' was next at 55%.

The factor analysis of these responses identified four statistically significant factors (supporting information Table S1). Based on the estimated factor loadings (supporting information Table S2), the items most strongly associated with the first factor are 'public safety', 'protecting water quality', 'family and worker safety', 'protecting wildlife', 'crop marketability' and 'protecting beneficial insects'. These items all have a 'human and environmental safety' theme, which is the label we assigned. The items most strongly associated with the second factor are 'convenience', 'reducing equipment wear and tear', 'simplicity', 'saving time and labor', 'flexibility' and 'reducing scouting'. All these items are summarized by the label 'time and ease'. Items most strongly associated with the third factor are 'having consistent insect control', 'having long-lasting insect control', 'protecting yield', 'improving crop stand' and 'improving plant health', which are summarized by the label 'plant health risk'. The fourth factor is most strongly associated with the 'being able to plant early' and 'replant or other product guarantees' items and so is labeled 'planting risk'.

3.3 Pest management practice adoption, level of adoption and value

Table 5 summarizes the probit regression results (column 2) for the probability of a farmer using an insecticide seed treatment on soybean in 2013, tobit regression results (column 3) for the proportion of soybean area planted with treated seed for those farmers who used it in 2013 and the interval regression results (column 4) for a farmer's stated added value of all the benefits and costs of seed treatment for those farmers who used it in 2013. Regression coefficients and absolute t-statistics are reported for the farm and farm operation characteristics and factor scores measuring the intensity of each farmer's consideration of the four statistically significant factors. A Wald test of the joint significance of all the regression control variables is reported, as is a test of the null hypothesis of no state fixed effects, although individual state fixed effects are not reported to conserve space. Finally, the number of observations for each regression is reported.

Of the 494 respondents that indicated whether or not they used an insecticide seed treatment, 426 (86.2%) provided enough information on the control variables to be included in the probit analysis. Two-thirds of the respondents that were lost did not provide complete information on the 20 items required for the factor analysis. Of the 254 respondents who indicated that they used an insecticide seed treatment, 225 (88.6%) provided enough information to be included in the tobit analysis for the proportion of soybean area planted with treated seed, while 207 (81.5%) provided enough information to be included in the interval regression analysis of the added value of treated seed. Much of the sample size difference between these two regressions is due to farmers indicating that they did not know the added value of treated seed.

The only control variable that was statistically significant for a farmer's decision to use treated seed was years of farming experience. The negative coefficient implies older, more experienced farmers were less likely to use treated seed, a relatively new pest management option for them. The state fixed effects were also statistically significant, indicating that the 2013 seed treatment adoption rate varied systematically across states.

The proportion of the soybean area planted with treated seed for those farmers who used it was significantly lower for farmers in counties with higher average yields and where NASS did not report an average yield in 2013. The proportion of the soybean area planted with treated seed was also positively and significantly related to a concern for 'plant health risk' (factor 3), indicating that

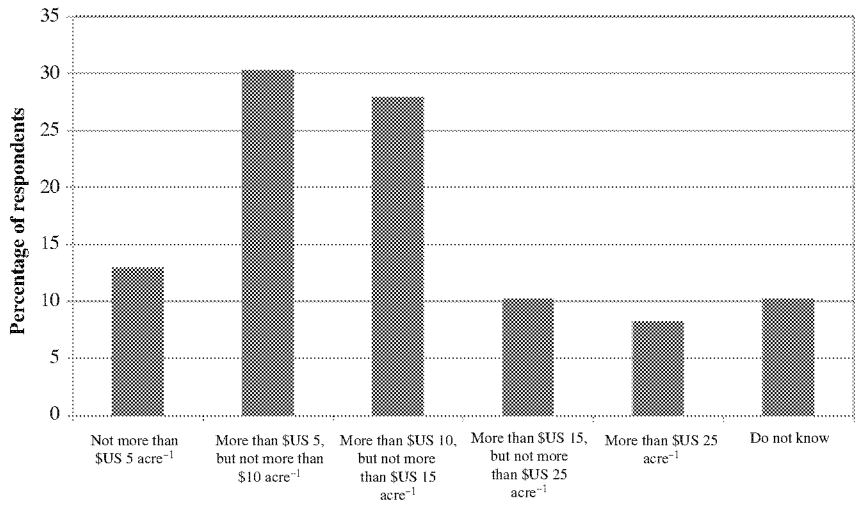

Figure 3. US soybean farmer responses about the additional value of using insecticide seed treatments in 2013 based on a telephone survey (responses = 254) with units as in original survey (values are US$ and 1 acre equals 0.4047 ha)

Table 4. Importance rankings for factors affecting insect pest management decisions of US soybean farmers in 2013, based on responses to a telephone survey

Factors[a]	Not important	Somewhat important	Important	Very important
		Percentage of surveyed farmers		
Family and worker safety	0.8	5.1	26.9	67.3
Protecting yield	0.4	6.7	30.7	62.2
Having consistent insect control	0.8	7.5	34.0	57.7
Cost	1.8	12.3	29.8	56.1
Protecting water quality	1.4	9.5	33.7	55.4
Crop marketability	2.6	14.6	30.4	52.3
Public safety	2.6	13.3	32.5	51.5
Improving crop stand	2.0	12.8	36.3	48.9
Having long-lasting insect control	2.0	12.2	37.4	48.4
Improving plant health	0.2	11.3	40.4	48.1
Protecting beneficial insects	4.3	20.5	34.8	40.4
Saving time and labor	3.2	20.0	39.6	37.2
Protecting wildlife	4.9	22.9	37.7	34.6
Reducing equipment wear and tear	5.7	26.6	34.3	33.3
Being able to plant early	10.2	26.7	31.8	31.4
Simplicity	4.3	24.2	41.2	30.3
Flexibility	2.7	27.9	40.2	29.3
Convenience	4.3	26.9	40.2	28.6
Replant or other product guarantees	10.0	28.7	36.8	24.6
Reducing Scouting	15.5	31.5	32.1	20.9

[a] The number of responses for each factor varied from 495 to 488, with 455 individuals responding to all 20 factors.

farmers who considered 'having consistent insect control', 'having long-lasting insect control', 'protecting yield', 'improving crop stand' and 'improving plant health' as important to their insect management decisions tended to use more insecticide-treated seed, as would be expected given treated seed's reported benefits. Significant state fixed effects again reveal systematic differences across states in the proportion of soybean planted with treated seed.

The added value of insecticide-treated seed to the farmers who used it was significantly and negatively related to a farmer's total crop area. It was significantly lower in counties with higher average yields and where NASS did not report an average yield in 2013. Combined with the results on the proportion of treated acres, the emerging picture is one where farmers with larger operations in locations with relatively high soybean productivity perceive less value added from insecticide-treated seed and use less of it. Farmers who considered 'human and environmental safety' (factor 1) and 'time and ease' (factor 2) as important for their insect management decisions valued insecticide-treated seed significantly less. While the first of these results is intuitive – farmers who are more concerned about human and environmental health discounted the benefits of insecticides, the second result is at first puzzling. However, recall that flexibility is an important item related to the 'time and ease' factor (supporting information Table S2), and,

Table 5. Parameter estimates (absolute *t*-statistics in parentheses) for the probability of using soybean insecticide seed treatments, proportion of treated area, added value ($US ha^{-1}) of treatments and average soybean yield (kg ha^{-1})[a]

Regression variable	Probability of use	Proportion of treated area	Added value($US ha^{-1})	Average soybean yield (kg ha^{-1})
Treated seed (1 = Yes)				128.0* (1.87)
Farmer and operation characteristics				
Education (years)	0.0038 (0.10)	−0.018 (0.71)	0.54 (0.82)	10.7 (0.65)
Years farming (years)	−0.013** (2.18)	0.0047 (1.14)	−0.082 (0.94)	−2.19 (0.80)
Total crop area (1000 ha)	0.022 (0.21)	0.049 (0.73)	−1.95** (2.14)	−45.3 (1.28)
2013 average county yield (kg ha^{-1})	0.00002 (0.11)	−0.00035*** (3.43)	−0.0056* (1.85)	0.88*** (10.89)
2013 unreported county yield (1 = Yes)	−0.56 (0.93)	−1.1*** (2.84)	−24.5** (2.43)	2287.0*** (8.04)
Factor scores				
Human and environmental safety	0.13 (1.37)	0.080 (1.19)	−2.91* (1.77)	−13.6 (0.31)
Time and ease	−0.0038 (0.04)	0.079 (1.22)	−2.77* (1.76)	10.2 (0.25)
Plant health risk	−0.018 (0.19)	0.17** (2.28)	2.73* (1.78)	73.7 (1.60)
Planting risk	0.17 (1.38)	−0.069 (0.92)	−1.90679 (0.94)	10.89 (0.20)
Standard deviation		0.51***	13.5***	
R^2				0.497
Wald regression significance χ^2 (22)	39.96**	86.30***	90.20***	
No state fixed effects χ^2 (13)	29.97***	30.63***	42.82***	0.89
Observations	426	225	207	416

[a] *** Significant at 1%, ** significant at 5%, * significant at 10%.

relative to foliar applications, insecticide seed treatments are not as flexible because they have to be used at planting before knowing what or if insect pests are going to be a problem. Consistent with the proportion of area treated results, concern for 'plant health risk' (factor 3) was significantly and positively related to the added value of insecticide-treated seed, which also is intuitive given treated seed's function. Again, significant state fixed effects reveal systematic differences in added value across states.

The results in Table 5 can be used to obtain state-level and aggregate estimates for all 14 surveyed states for the probability of a farmer using an insecticide seed treatment, the proportion of soybean area planted with treated seed given its use and the added value of treated seed given its use, taking into account the survey sample design (see the supporting information). These results are reported in Table 6. The estimated probability of seed treatment use ranged from a low of 0.349 in Wisconsin to 0.908 in Mississippi, with an aggregate average for all 14 states equal to 0.574. The estimated proportion of soybean area planted with treated seed ranged from a low of 0.754 in Michigan to a high of 0.958 in Iowa, with an aggregate average for all 14 states equal to 0.898. The estimated added value for farmers who used treated seed ranged from a low of $US 18.10 ha^{-1} in Michigan to a high of $US 35.21 ha^{-1} in Nebraska, with an aggregate average of $US 28.04 ha^{-1}. These results confirm and explicitly illustrate the significant and systematic difference in seed treatment use and added value across states identified in Table 5.

3.4 Yield impact of pest management practice adoption

The OLS relationship between yields, use of insecticide-treated seed, farmer and farm operation characteristics and non-monetary factors are reported in column 5 of Table 5 (see the supporting information for a summary of the instrumental variable analysis). Table 5 also reports the R^2, test for statistical significance of the state fixed effects and the sample size. Intuitively, the reported average yield was significantly higher in counties with higher average yields and significantly positive in counties where NASS did not report an average yield in 2013. Significantly higher yields were also reported by farmers who used insecticide-treated seed. State fixed effects were not statistically significant, nor were any other control variables.

These results imply that farmers who chose to use insecticide-treated seed on average had 128.0 kg ha^{-1} higher yields than farmers who chose not to use treated seed. With an average yield of 3165 kg ha^{-1} for those using a seed treatment, this additional yield amounts to more than a 4.0% advantage. The farm-level, marketing-year average soybean price was $US 477.75 Mg^{-1} in 2013,[44] which suggests the added revenue to soybean farmers who used seed treatments was $US 61.15 ha^{-1}. The national average cost of an insecticide seed treatment for soybean was $US 18.95 ha^{-1} for 2010–2012.[2] Subtracting this cost from the $US 61.15 ha^{-1} value for the added yield implies a return over cost of $US 42.20 ha^{-1}, which is comparable with the estimate of $US 28.04 ha^{-1} in added value based on farmer responses to the direct value question (Table 6).

These results are also comparable with other yield benefit and value estimates based on small-plot data. For example, a yield meta-analysis of 170 site-years of small-plot data from 2005 to 2014 for four southern states reported an average yield advantage of 132.0 kg ha^{-1}, worth an estimated $US 31 ha^{-1}.[30] Also, a yield meta-analysis of 298 studies from multiple states and provinces reported an average yield benefit of 3.6% for neonicotinoid seed treatments in soybean.[31] However, a wide range of yield advantages have been documented by individual studies. As expected, under low soybean aphid pressure, no significant difference is usually found.[22,61–63] For sites and years with substantial aphid pressure, significant yield advantages are found for neonicotinoid seed treatments.[22,63,64] For example, 18 site-years of small-plot data from six locations in three states (Iowa, Michigan and Minnesota) for 2005–2007 found a 95 kg ha^{-1} yield advantage, or a 7.5% advantage.[64] Similarly, analysis of small-plot data from nine locations in Wisconsin for 2012–2013 across a range of seeding densities reported a 227.0 kg ha^{-1} or 6% yield advantage,[25] while analysis of data from three locations in New

Table 6. Estimated probability of soybean seed treatment use, proportion of soybean area treated and added value ($US ha^{-1}) of using treated soybean seed by state and pooled across states (95% confidence interval in square brackets)[a]

State	Probability of use	Proportion of treated area	Value ($US ha^{-1})
All 14 states	0.574 [0.519, 0.628]	0.898 [0.871, 0.925]	28.04 [25.65, 30.43]
Arkansas	0.514 [0.247, 0.781]	0.756 [0.569, 0.942]	22.64 [18.45, 26.83]
Illinois	0.587 [0.439, 0.736]	0.891 [0.814, 0.968]	27.85 [22.18, 33.52]
Indiana	0.615 [0.404, 0.826]	0.949 [0.890, 1.000]	29.83 [25.03, 34.64]
Iowa	0.529 [0.378, 0.681]	0.958 [0.914, 1.000]	29.51 [23.89, 35.14]
Kansas	0.542 [0.329, 0.755]	0.944 [0.866, 1.000]	33.1 [26.11, 40.10]
Michigan	0.62 [0.393, 0.847]	0.754 [0.660, 0.847]	18.1 [12.85, 23.36]
Minnesota	0.384 [0.194, 0.573]	0.83 [0.718, 0.943]	27.92 [22.44, 33.39]
Mississippi	0.908 [0.779, 1.037]	0.757 [0.564, 0.950]	19.25 [12.96, 25.54]
Missouri	0.545 [0.369, 0.721]	0.905 [0.821, 0.988]	34.77 [22.19, 47.34]
Nebraska	0.604 [0.413, 0.795]	0.881 [0.742, 1.000]	35.21 [22.30, 48.12]
North Dakota	0.463 [0.226, 0.700]	0.943 [0.868, 1.000]	22.99 [16.27, 29.72]
Ohio	0.903 [0.792, 1.014]	0.951 [0.878, 1.000]	32.44 [28.87, 36.01]
South Dakota	0.635 [0.385, 0.884]	0.958 [0.886, 1.000]	18.45 [12.78, 24.13]
Wisconsin	0.349 [0.118, 0.580]	0.818 [0.614, 1.000]	23.6 [17.07, 30.13]

[a] Details of these calculations are provided in the supporting information.

York for 2009–2010 reported a 4% yield advantage across a range of seeding densities.[65]

Overall the results presented here suggest that econometric analysis of survey data can provide reasonable estimates of the value of pest control technologies, comparable with small-plot data. Not only must the biological information be appropriately incorporated into the analysis, but also the surveyed farmers should understand these technologies based on their experience across multiple years and many fields, and the observational data must be appropriately collected and analyzed to account for potential endogeneity.

4 CONCLUSION

The primary purpose of this research was to gain a better understanding of the value of neonicotinoid seed treatments to US soybean farmers. This goal was accomplished using a telephone survey of 500 commercial-scale US soybean farmers from 14 US states.

Our first finding was that US soybean farmers consider the soybean aphid to be by far the most important insect pest to manage, although to some farmers other pests are also important, such as beetles, mites and stink bugs (Table 2). Secondly, neonicotinoid seed treatments were the most widely used insecticide in US soybean in 2013. About half of the surveyed farmers used neonicotinoid seed treatments when planting soybeans in 2013, on 87% of their planted area on average, so that 45% of the surveyed soybean-planted area was planted with treated seed (Table 3). Comparable data for foliar applications showed 23% of US soybean farmers using them on 70% of their planted area on average, so that in total, 16% of the surveyed soybean area received a foliar insecticide in 2013, mostly pyrethroid and organophosphate insecticides.

Farmers were asked to rank the relative importance of 20 different factors when making their insect management decisions (Table 4). Using factor analysis, we found that human and environmental safety was an important concern for US soybean farmers (supporting information Tables S1 and S2). This finding likely contributes to the greater reliance of US soybean farmers on neonicotinoid seed treatments rather than foliar applications. Farmers perceive neonicotinoid insecticides as relatively safer to use and causing less exposure to humans and the environment than foliar applications,[66] plus neonicotinoid insecticides have been categorized as a reduced-risk conventional insecticide by the US EPA.[5] Given concerns with the environmental risks associated with neonicotinoid insecticides, these results regarding farmer concern for human and environmental safety suggest that US soybean farmers would be open to changing insect management if the alternatives were both effective and perceived as safer than foliar applications.

Our main results pertain to the ongoing debate and policy decisions regarding the value and yield benefits of neonicotinoid seed treatments for soybean. A benefit assessment is part of the mandated process the US EPA uses when balancing risks and benefits for pesticide registration decisions under FIFRA.[19,67] Based on an examination of the published research from small-plot studies, the yield benefit and value of insecticide seed treatments to US soybean farmers have been questioned by the US EPA.[68] Our results directly contribute to this process. We use farmer survey data to estimate the value of seed treatments both directly and indirectly. Asking farmers directly how much value insecticide seed treatments provide to them yields an estimate of $US 28.04 ha^{-1} for the 2013 crop (Table 6). An indirect approach that used self-reported average yields estimated that farmers using a seed treatment had average yields that were 128.0 kg ha^{-1} larger than those not using a seed treatment, which is a 4.0% increase and, using 2013 prices, had an estimated net value of $US 42.20 ha^{-1} in 2013. These estimates based on different data and methods are consistent with one another and other meta-analyses,[30,31] suggesting a robust finding. Hence, we conclude that the average value of insecticide seed treatments for the US soybean farmers that used them in 2013 was around $US 28–42 ha^{-1}, net of the cost of the seed treatment.

ACKNOWLEDGEMENTS

This research was funded in part by AgInfomatics, LLC of Madison, Wisconsin, with financial support from Bayer, Syngenta and Valent.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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